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Deployment of Inflatable Space Structures: A Review of Recent Developments.

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Abstract

This paper reviews recent advances and future challenges in analytical and experimental methods for understanding and verifying the deployment of inflatable structures in space. Concepts for free and controlled deployments are discussed and examples are cited. Prior experiences with ground and flight experiments are examined and the promise of predictive analytical models is reviewed.

In the early stage of inflatable developments, analytical simulations of deployment were noticeably lagging because of the high degree of problem complexity. However, recent experiences with a number of engineering and phenomenological models show that these models are particularly useful in explaining the physics of deployment. The paper concludes with likely future directions on the best use of deployment tests and analytical simulations to enhance the low mass and volume advantages of inflatables with greater deployment reliability, and at the same time, minimize the use of massive complex control devices.

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1. Introduction

Because of dimensional constraints dictated by the finite size of the launch shroud, large spacecraft appendages must be stowed during launch then deployed once on-orbit. In the past, a variety of innovative electro-mechanical systems have been used to deploy masts, antennas, solar arrays, and other components for space applications. More recently, however, significant efforts have been devoted to the development of alternate approaches that utilize inflatable structures for space applications. These developments have claimed much promise to the point that many space missions have proposed large inflatable structures for lightweight radiometers, radars, deep space antenna, solar concentrators, optical communication systems, and telescopes. Among the most significant advantages of inflatable structures over their traditional electro-mechanical counterparts are their low stowed volume, mass, cost, good damping and good thermal properties. However, equal or greater deployment reliability of inflatables over electro-mechanical systems is yet to be demonstrated. It is true that all deployable systems, including inflatables, can potentially fail. Whenever there is movement of parts, there is less reliability and greater risk – regardless of heritage or uniqueness of construction. In the past, space systems experienced their highest failure rate during deployment, but have typically performed well once deployed properly.

With inflatable structures, the stake is even higher, since their structural load carrying ability is commensurate with their state of deployment. The stiffness and consequently, the load carrying ability of an inflatable component are synonymous with its degree of inflation. This intrinsic attribute of inflatables is particularly challenging. It attaches special significance to validating their deployment reliability, even though deployment validation by ground experiments is rather difficult - if not impossible. Furthermore, ensuring proper deployment sets the stage for achieving accurate surface figure for ultra-lightweight precision reflectors, and subsequently for implementing higher order functions such as actively controlling the system dynamics.

In consideration of the forgoing observations, this paper will focus on reviewing recent developments and future challenges in analytical and experimental techniques for understanding and substantiating the deployment of inflatable structures in space. The related problem of dynamic characterization of already-inflated structures has been reviewed in [1], and is not considered here for two reasons. First, the dynamics of inflation involve phenomena that are different from those that dominate already-inflated structures. Second, already-inflated structures have a weaker degree of non-linearity - and are therefore - considerably more analyzable, easier to characterize, and have reached a higher degree of technological maturity than structures in states of partial inflation.

2. Classification of Deployment

Deployment schemes that have been proposed for inflatable structures may be broadly classified dynamically as unrestricted free deployment, and passively controlled deployment. This classification is closely related to details of the initial packaging, and the mechanisms used during inflation to control the rate of release of the inflated and yet-to-be-inflated segments of the structure. In free deployment, the inflated or partially inflated segments of the structure are not restrained from moving about freely in space once released. In controlled deployment, however, only the inflated segments are allowed to deploy in space. Since fully inflated segments have much higher stiffness than partially inflated segments, systems with controlled deployment tend to be dynamically more stable.

For long and highly flexible tubular structures, free inflation deployment could be unpredictable and unstable. This was clearly evidenced by the on-orbit deployment of the Inflatable Antenna Experiment (IAE) flown in May 1996. It is important to note, however, that not-all free deployment schemes are unstable. For example, stable free deployment of a long flexible boom, regardless of whether it is rolled up or Z-folded before deployment, can be achieved when the leading portion of the boom has sufficient momentum through the entire deployment process. This requirement was recognized by the IAE design team [2]. In the IAE design, the leading (top) end of each of the three Z-folded, long (92-foot) support struts was connected to the stowed canopy/torus bundle. A set of pre-strained kick-off springs and a throw plate were incorporated for the purpose of propelling the canopy/torus bundle out of the canister with initial momentum that was sufficiently high to maintain stable deployment of the struts. When the IAE deployment process was analyzed before flight, the throw plate and canopy/torus bundle were assumed to be a rigid and homogeneous brick-shaped block and the possible loosening-up of the bundle was not seriously considered. However, due to the residual pressure in the thin-film canopy, the canopy/torus bundle loosened as soon as the lid of the containing canister opened in space vacuum. When the kick-off springs were actuated, impulse was imparted - not to the whole bundle - but to a small fraction of it in immediate contact with the throw plate. This resulted in that the initial momentum was not sufficient to unfurl the struts in a stable manner. In 1997, Tsoi [3] successfully simulated both stable and unstable free deployments of Z-folded and rolled booms.

Following the IAE experiment, attentions turned away from free deployment concepts to controlled deployment, where resistive devices are used to control the rate of inflation. One of the early concepts [4], proposed to use collapsible diaphragms to divide a long inflatable tube into a series of sectional compartments. These diaphragms can be flexible enough so that the tube can still be Z-folded or rolled for high packaging efficiency. Deployment of the tube can then be initiated by inflating one compartment at a time until it reaches the operating pressure and attains the desired stiffness. At this point, the flow of inflating gas, regulated by check valves or burst disks installed on the diaphragms, will start to inflate the next compartment of the tube. This "sequential" inflation process can achieve stable and predictable deployment of a tubular inflatable structure. Another concept, also described in [4], suggested the use of coil springs of relatively low spring constants. The coil springs are to be embedded in the walls of an inflatable tube that is rolled up before deployment. A stable deployment of the tube is achieved by balancing the inflation pressure and the restoring forces of the springs.

With the understanding that stability and controllability of deployment can be achieved by providing positive resistive forces to balance the inflation pressure, many innovative design concepts emerged. For example, embedded coil springs can be replaced by Velcro® strips glued to the outside of the tube wall of rolled booms. In addition to being lightweight and easy to install, Velcro® strips offer two distinct advantages over embedded springs. First, booms with Velcro® strips can be packaged in both rolled and Z-folded configurations. Second, the Velcro® strips will not impose returning forces on the deployed tube when the inflation deployment is completed. It is worth mentioning that Velcro® strips have had space flight heritage. In the Mars Pathfinder mission, Velcro® strips were used to slow down the deployment of the landing ramps for the rover.

Another early example of deployment control design, proposed and developed at L'Garde, involves the use of a mandrel. During deployment, the inflatable tube is forced to go over an internal guiding mandrel and develop frictional forces to balance the inflation pressure. Application of mandrel-guided approach to control the inflation deployment of a space rigidizable truss has been successfully demonstrated. However, this technique can be applied only to inflatable components with prismatic shapes, and not to a torus or lenticular shape.

More recently, a wire brake design was developed by ILC-Dover. This design is currently being refined for the application to an inflatable sunshield space experiment (ISIS) scheduled to be flown in the Space Shuttle in 2001.

Thus, while free deployment schemes usually require less weight, complexity, and initial cost, they may be less stable if not properly designed. On the other hand, inflatables deployed with the aid of passive control devices are more likely to be dynamically stable – but at the expense of more mass, complexity, and cost.

3. Deployment Experiments

As with all systems intended for use in space, the reliability of deployment of inflatable structures must be validated by an appropriate combination of analyses, ground experiments and flight experiments. In this section, we focus on ground and flight experiments.

3.1 Ground Experiments

Experiments have been routinely performed in-the-laboratory-setting to characterize or validate specific aspects of the deployment process. As such, some parameters are intentionally controlled in order to yield specific measurements. The experiment of Ref. [5] to measure equivalent deployment forces or torques is a good example of parameter determination in support of an analytical model. Other examples include testing the functionality of the inflation system, repeatability of a particular folding/unfolding scheme, as well as other tests to calibrate deployment analysis [6, 7]. The purpose of the Inflatable Sunshield In Space (ISIS) is to verify the design of the inflation deployment system [7]. Major components of the ISIS engineering model include four inflatable/rigidizable booms and several layers of thin membrane. The diamond-shaped membrane is stretched at four corners by inflatable/rigidizable booms made of aluminum laminate. After deploying the booms at a relatively low internal pressure, the pressure is increased to stretch the aluminum beyond the material yield point. This imparts rigidity to the booms, and inflation gas is no longer required to maintain stiffness. Figure 1 shows the deployed Sunshield after a sequence of deployments that involved inflating the vertical, then the horizontal struts. Among the lessons learned from this experiment was that static electricity between membrane layers could be strong enough to prevent membranes from deployment. Second, the stretched aluminum laminate boom concept was not suitable for the present application because cracks developed on the boom during the process of repeated flattening, roll-up and deployment.

Another example of a ground experiment to test functionality was conducted in the course of developing the 5-meters inflatable/ rigidizable Carpenter-Tape Reinforced (CTR) Aluminum Laminate booms for the Inflatable Synthetic Aperture Radar (ISAR) [8]. The inflatable/ rigidizable booms need to be flattened and rolled up at least once before launch. Eventually, they will be inflated in space to carry structural loads. It is important, therefore, to assess the rigidized boom strength as a function of its prior pressurization history. The results clearly indicated that the deployment pressure and length of pressurization time did affect the functionality and strength of these booms.

3.2 Flight Experiments

Prior to full inflation, structural components have little or no intrinsic stiffness. This makes ground testing of the inflation process - in gravity and air - extremely difficult, if not impossible. In recognition of this, the Inflatable Antenna Experiment (IAE) was conducted in May 1996. The successful completion of this experiment has driven the design of subsequent inflatable concepts, but at the same time, it has led to several safety and mission reliability concerns. The deployment procedure was planed to have five steps [9] as shown in Figure 2. The first step is the free fly of the whole system in stowed configuration. The second step is the opening of the inflatable antenna container cover; the third step is the shooting out of the inflatable antenna by several kick-off springs installed in the container; the fourth step is partially inflated; and the fifth step is completely inflated. Unfortunately, residual gas inside the three struts pushed the inflatable antenna out of the container before the kick-off springs were initiated. Figure 2 illustrates the planned and actual deployment sequence. The results emphasize the necessity of verifying the reliability of inflatable deployment prior to flight. Had there been other appendages and subsystems, which are normally included in a space system (e.g. sensors, instruments, power, and communication), irregularities experienced in this test would have easily caused entanglement, and possibly irrecoverable mission failure.

4. Analytical Simulations of Deployment

4.1 Problem Complexity

Problems involving interactions between computational fluid dynamics and computational structural dynamics have traditionally been analytically intractable. Even within the realm of small deformations, sensitivity of the governing equations (e.g. Navier-Stokes) to accurate description of the deformed aeroelastic surface has been a major computational difficulty [10, 11]. For similar reasons, the dynamics of the inflation process in inflatable structures is also computationally intractable.

To begin with, the inflation dynamics start with the packaged state - which is almost singular due to the vanishingly small stiffness of the un-pressurized flexible membrane. Furthermore, the nature of the packaging scheme (e.g., folding or rolling, with or without passive constraints) will influence subsequent states of deployment. Even seams, folds, wrinkles, and other imperfections in the membrane are important physical features, which are extremely difficult to describe mathematically with accuracy. Yet they could have profound effects on how membranes unfold. In the packaged state, all surfaces of the inflatable membrane are in contact. As inflation ensues, the internal flow of pressurizing gas and the external forces of surface contact will interact in a nonlinear manner with the inflatable membrane enclosure, causing various segments to undergo complex nonlinear large displacements and large angles, possibly with intermittent bifurcation. The final state of deployment could be stable or unstable. These complexities have induced many researchers to seek simplified mathematical models to help understand and predict how inflatables deploy. In the following, these simplified models are broadly classified into two groups: engineering models, and phenomenological models.

4.2 Engineering Models

Motivated by the need to understand the basic mechanisms of how membranes inflate and deploy, several simplified engineering models have been introduced that attempt to emulate the inflation mechanisms by simple mechanical analogues with limited parameters. As an example, Fay and Steele [5,12] developed a constant curvature model, which approximates the equivalent forces of static pinching and torque on a cylindrical tube initially folded or rolled. The static pinch force, F_{fold}, approximates the dominant resistive force at the fold line during inflation of a Z-folded tube, and the static torque, T_{roll}, approximates the inflation-induced torque that causes unfurling of a rolled tube. These are:

$$F_{fold} = w(2R_2 + R_1)P \tag{1}$$

$$T_{roll} = wR_2(R_{1t} + R_{1b})P \tag{2}$$

where R_1, R_2, R_{1t}, R_{1b} are radii of curvature, $w =$ width of un-inflated tube, and $P =$ internal pressure. Although equations (1) and (2) over-estimate their experimental static counterparts to within a factor of 1.7 to 3.1, they still provide a useful parameterization of some of the major forces of inflation. An application of the above results to deployment of a rolled tube was implemented in [13], wherein the system is treated as a single variable mass subject to a torque proportional to pressure.

In another approach, Clem, et al [14] considered the inflation of rolled tubes supporting a central solar array blanket. The tubes were modeled as a system of rigid links connected by flexible rotational springs and dampers. The spring stiffness is assumed to be a nonlinear (smoothed step) function of the angular deformation, and the effect of pressure is accommodated by arbitrarily scaling the stiffness of all springs by a function ranging between zero and one.

Most mechanical models have no analogue to the phased build up of pressure as the gas flows inside various sections of the inflatable cavity. Yet, it is the presence of this phased pressure distribution (in time and space) that leads to realistic modeling of the inflation process. This is further explored in the following section.

4.2 Phenomenological Models

As distinguished from mechanical models, phenomenological inflation models attempt to capture the effect of the inflating gas as it flows into the inflatable cavity. Initial work in this area is due to Wang & Nefske [15] and is concerned with the impact of airbag inflation on occupants in automobiles. The airbag inflation is modeled as a single cavity connected to an inflator through an orifice. As the gas flows across the orifice, the volume changes and the pressure in the cavity also changes with time. The rate of flow of mass of gas dm_{mn} across the orifice can be represented by a one-dimensional quasi-steady flow [16, 17], expressed for a subsonic flow by:

$$dm_{mn} / dt = kA_{mn}P_d[(1/GT)(2\gamma/(\gamma-1)) \times (P_o/P_d)^{(\gamma-1)/\gamma}((P_u/P_d)^{(\gamma-1)/\gamma}-1)]^{1/2} \tag{3}$$

where: P_o, P_u, P_d are respectively the initial pressure, upstream pressure, and downstream pressure, γ = specific heat ratio, G = gas constant, T = gas temperature, and k = orifice coefficient. Similarly, when the flow is sonic, it can be approximated in one dimension by:

$$dm_{mn} / dt = kA_{mn}P_d[(1/GT)(2\gamma/(\gamma+1))^{((\gamma+1)/(\gamma-1))} \times (P_u/P_d)^{(\gamma+1)/\gamma}]^{1/2} \tag{4}$$

Variations on the above inflation model have been implemented in several proprietary and commercial crash dynamics codes such as CAL3D, PAM-CRASH/PAM-SAFE, and DYNA3D. Other diffusive gas models have been also proposed and used to study airbag – occupant interactions during car collisions [18-20]. Diffusive gas models attempt to account for localized effects of gas jetting, thereby introducing pressure variations on walls of the cavity, *but only in the vicinity of the orifice, which is otherwise assumed constant.* In a recent study, analysis using this feature was shown to correlate well with airbag deployment tests [21].

The first adaptation of the airbag inflation model to aerospace inflatable structures was made by Haug et al [22] to simulate the inflation and deployment of a space rigidizable antenna, and by Salama, et al [17] to simulate the landing dynamics on the surface of Mars. Since then, it has been recognized that although there are significant similarities between the mechanics of inflation of an automobile airbag and an inflatable space structure (e.g. booms), there are also significant differences that can render the simulation highly inaccurate if not properly addressed. Most important is the ability of the simulation to correctly capture the spatial and temporal pressure phasing throughout walls of the inflatable cavity. For the relatively small airbag cavity, the internal pressure is nearly identical at all locations, but exhibit considerable variations with respect to location and time in the inflation of a large or long structural component. The inability of the model to capture this variation has been responsible for some unrealistic simulations, for example - causing a tube to deploy at the same rate at both ends - even though it is being inflated from one end only [14, 22].

A good approximation of the pressure distribution $P(x,y,z,t)$ on walls of the inflatable cavity can be achieved by introducing further refinement of the airbag model [23]. As shown in the schematic of Figure 3, the continuum of enclosed volume may be discretized in its stowed state into a set of connected smaller enclosures or finite volumes. Common artificial baffles, which can vent to each other through artificial orifices, provide continuity of the flow between these finite volumes. Starting with the stowed state as initial condition, the inflating gas enters the first finite volume, and in turn, flows to other contiguous volumes through the artificial orifices. Among other variables, the amount of flow between typical finite volumes m and n is a function of the orifice area A_{mn}, the magnitude of which can be allowed to vary in proportion to the local area of the associated baffle. In the initial stowed state, all orifices are given infinitesimally small areas. As inflation progresses, these areas are gradually increased to equal the local inflated baffle areas at full inflation. If there are folds in the stowed configuration, it is expedient to locate some of the artificial baffles/orifices at the fold lines, since fold lines provide natural constriction of the flow. If there are no fold lines, discretization of the enclosed volume and location of the baffles should be chosen judiciously to emulate the actual flow. Leakage to the outside, if present, can be modeled similarly by venting the finite volume(s) in question to the open external volume.

Depending on the type and direction of flow, either of the nonlinear Equations (3) or (4), can be integrated numerically for each pair of volumes m and n to calculate the mass of gas $\Delta m(t)$ transferred between them at each discrete time t in the simulation. Assuming constant density, the corresponding change in volume of each finite volume, say m, due to gas flow is computed as $(\Delta V_f(t))_m$. Other volumetric changes, here collectively referred to as $(\Delta V_v(t))_m$, arise from large deformations of the membrane shell itself, partly due to flexibility of the skin, or due to contact forces between the inflated surfaces, or any other source of deformation. The total change in volume of finite volume m is the sum of all aforementioned effects:

$$\Delta V_m(t) = (\Delta V_f(t) + \Delta V_v(t))_m \tag{5}$$

The corresponding updated pressure is then found for a typical finite volume from:

$$P_m(t) = P_o[V_o/(V_o - \Delta V_m(t))]^\gamma \qquad (6)$$

The forgoing spatial discretization of the gas flow permits a tractable computation of the instantaneous pressure $P_m(t)$ as function of time, for every finite volume $m = 1,...,N$. As inflation progresses, the computed pressure values are applied to the walls enclosing the inflatable finite volume, and one can propagate computation of the deformations dynamically to the next time step in the simulation. The walls themselves can be modeled as thin-walled shells, either analytically in closed form, or by the usual finite element technique. Consistency between both of the finite element and finite volume models should be maintained, at least geometrically, but the degree of element refinement does not need be the same. This methodology has been successfully employed in simulating the deployment of cylindrical tubes from both Z-folding and from rolled state [23], and is now being extended to other complex geometry.

5. Conclusions & Future Challenges

In comparison to mechanically deployed systems, most of the appealing features of inflatable structures (e.g. low packaging volume and lightweight) stem from the absence of mechanical deployment aids. Yet, in reaction to the IAE experience, attentions turned away from free deployment - where almost no mechanisms are used - to the more stable passively-controlled deployment schemes. In the later, a variety of mechanical resistive and energy control devices are used – sometimes excessively. This adds undesirable mass and packaging volume, and makes inflatables less competitive with traditional mechanical systems. For future missions, such as ones combining inflatable components in the construction of a large solar sail, low-mass and simple deployment are critical features. Here, controlled deployment may not be suitable, and one may have to consider free deployment options.

Several analytical deployment models have been proposed. A number of these models have been employed successfully to explain the physics of membrane deployment. By combining results from laboratory experiments with analytical simulations, these models could provide guidance to the designer on how to maximize deployment stability with minimum use of massive control devices. This appears to be the next important step to maintain the advantages of inflatables over mechanical systems.

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Figure 1. Deployed sunshield after a sequence of strut inflations.

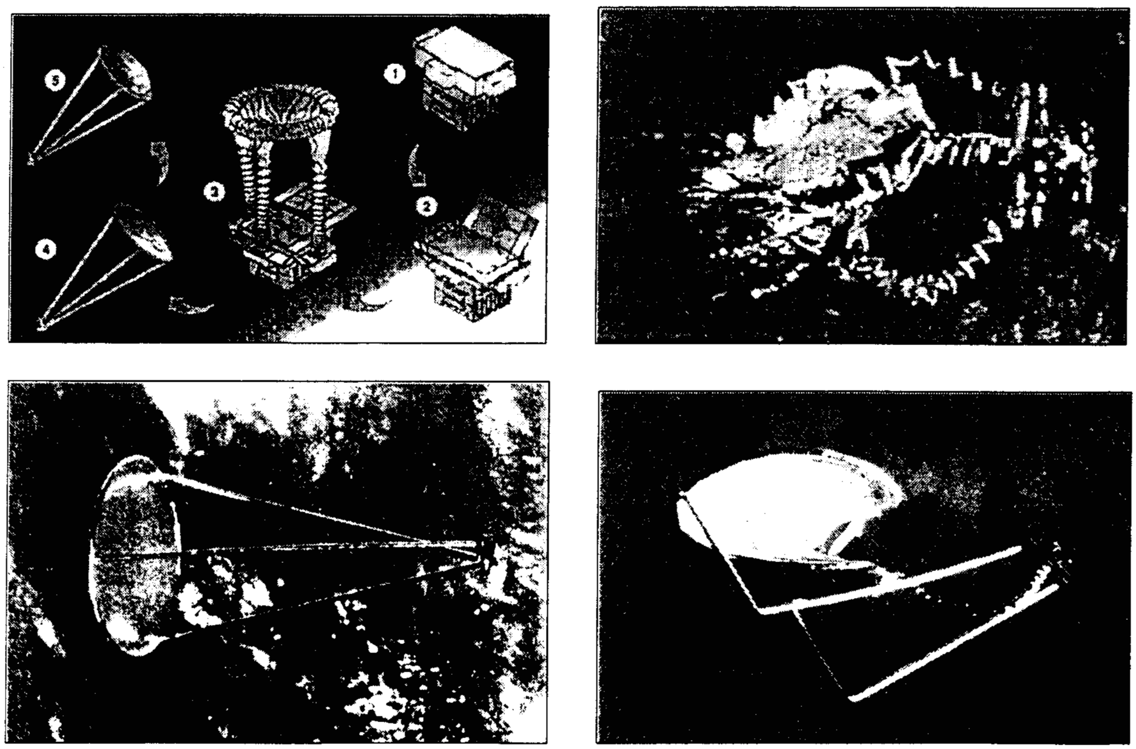

Figure 2. Various stages of planned and actual IAE deployment

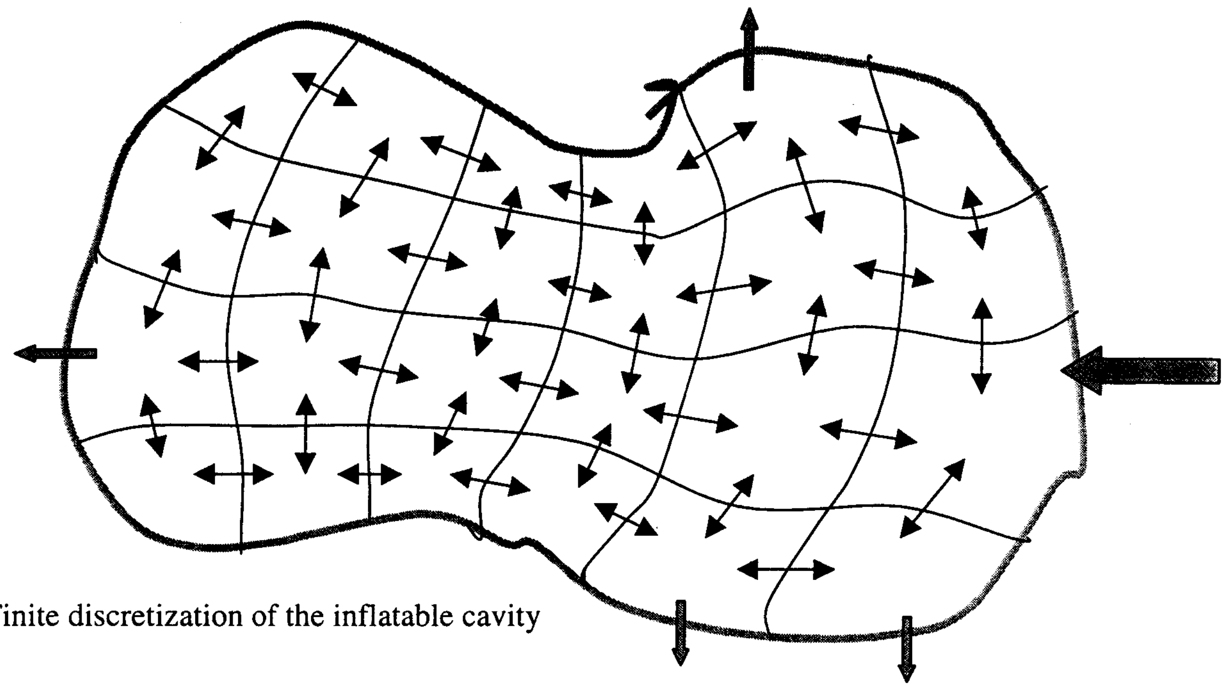

Figure 3. Finite discretization of the inflatable cavity